

# **LEGIBILITY NOTICE**

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although portions of this report are not reproducible, it is being made available in microfiche to facilitate the availability of those parts of the document which are legible.

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

TITLE: PF MAGNETIC DESIGN FOR THE 4MA REVERSED FIELD PINCH EXPERIMENT  
CPRF

LA-UR--87-3431

DE88 001831

AUTHOR(S): Robert F. Gribble and John D. Rogers

SUBMITTED TO: IEEE Meeting, Monterey, California, October 12-16, 1987

#### DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U S Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U S Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U S Department of Energy.

**Los Alamos** Los Alamos National Laboratory  
Los Alamos, New Mexico 87545

2500

## PF MAGNETIC DESIGN FOR THE 4MA REVERSED FIELD PINCH EXPERIMENT CRRF\*

Robert F. Gribble and John D. Rogers  
Los Alamos National Laboratory  
Los Alamos, New Mexico 87545

### INTRODUCTION

ZTH is to reach 2 MA by inductive energy transfer in 0.05 s, followed by power supply ramping to 4 MA in 0.4 s. Major and minor radii are 2.4 and 0.4 m. Copper for the poloidal field coils weighs 48 metric tonnes, the one-turn equivalent ohmic heating (OH) coil inductance is 1.90  $\mu\text{H}$ , and the OH coil rating is 15.4 MAT, 225 MJ, and 29.3 Vs at 60 kA. The normal operating OH current is 50 kA. Design of the coil for 60 kA provides a margin for uncertainties.

OH coils are connected in series and the combination is connected in parallel with four equilibrium field (EF) coils. With optimized location of all coils, this connection provides decoupling between the OH and EF coil sets so that the changing OH current does not affect EF winding current.

### DESIGN PHILOSOPHY

The ZTH PF coil arrangement and circuit is similar to that of the RFX experiment, and actually grew from the original Padova air core design proposed for the British RFX. In this concept the OH and EF coils are connected in parallel and located so that the two sets are decoupled, and the EF coil induced currents are directly proportional to plasma current with a magnitude to provide an initial passive equilibrium. Power required for equilibrium control in this design is minimized, a highly important consideration for the fast risetime of ZTH.

The Padova concept is similar to the original Doublet design, where, with proper placement of OH coils and a parallel connection of EF coils located close to the shaped vacuum vessel, the desired flux surface shape was obtained from the EF coil induced currents. In the limit of vanishing coil resistance this ideal geometry would preserve the desired flux surface for all time because with equal turns all coils must have and maintain the same flux, independent of plasma current. With nonzero resistance and open EF coils, the OH coils must be situated so that the OH flux returns outside the toroidal area enclosed by the EF coils to prevent diffusion into this area of OH fields, altering the flux surface. As plasma current increases, induced EF coil currents due only to plasma flux changes maintained the flux surface. Small power supplies compensated for resistive drops, and in addition, were used to produce small changes in the flux surface shape.

The RFX EF coils cannot be located on the vacuum vessel (liner) because of the shell and TF coils, but the same Doublet idea is achieved by shifting the circle on which the EF coils are located inwards so that a flux surface coincides with the liner. ZTH specifications on toroidal field (TF) error and diagnostic access prevent placement of any part of an EF coil closer than 30 cm from the liner with the result that location of EF coils on a shifted circle similar to that of the RFX design would require an unacceptably large OH and EF coil configuration. The solution to the ZTH magnetic design problem is the use of a nonlinear numerical optimizer program that simulta-

neously places OH and EF coils to minimize both equilibrium power supply and coil costs.

### ZTH MAGNETICS DESIGN CONSTRAINTS

There are many specifications (constraints) that strongly influence the ZTH magnetics design. The effects of most of the constraints are not mutually exclusive. Some of the more important constraints in roughly the order of impact are listed below.

1. Programmed current changes in the OH and EF coils must be capable of generating a 4-MA plasma current using reasonable models for plasma parameters. This criterion reduces principally to specifications on the plasma current risetime and available volt-seconds in the OH coils.
2. The diagnostic access must be adequate. The original specification that there be clear access to the liner horizontally at the midplane and vertically above and below the minor axis was too expensive for the equilibrium control system. The compromise allows 25 cm above and below the midplane looking horizontally in from the outside of the torus and 2.5 cm about the minor axis looking vertically.
3. Maximum radial deviation of the flux surface at the liner is  $\pm 5$  mm. This limit is imposed to control plasma-wall interactions and erosion of the graphite armor. Here deviation ( $d$ ) is defined as the greatest radial distance from the liner to the largest flux surface within the liner. The specification of  $\pm 5$  mm above is equivalent to a  $d$  value of 10 mm.
4. The size of the radial field error in the toroidal field is specified as a function of the toroidal mode number to control magnetic island size at the reversal surface.
5. The coil voltage and current must be within boundaries set by conventional high voltage and switching technology.
6. At plasma initiation there must be a field null near the axis and the field throughout the vacuum vessel must be less than 100 G.
7. A structure to support coils and load assembly must be low cost, easy to assemble, and allow modular placement of coils.
8. Within all other constraints, the total cost of the coils, switchgear, and power supplies should be minimized.

### THE ZTH MAGNETICS DESIGN COMPROMISE

The specification that most influenced the design of ZTH is the risetime requirement of about 50 ms arising from specification 1. Scaling results from ZT-40N show that the risetime for inductive energy transfer should be as fast as reasonably possible to reduce the consumption of poloidal flux required to reach 2 MA. Because of the fast current rise, power necessary to control equilibrium during the rise tends to be very large unless the doublet equilibrium scheme is employed so that equilibrium supplies only compensate for resistive losses and provide small adjustments to allow for variations of internal plasma energy. If the risetime were several seconds, the doublet scheme would not be necessary because EF energy could be supplied over the longer time with power supplies of modest size. A nondecoupled PF magnetics configuration for

\*Work performed under the auspices of the U.S. Department of Energy.

ZTH with 50 ms risetime would require more than 600 MW of equilibrium power. The chosen geometry requires 16 MW of equilibrium power to reach 2 MA and 70 MW for 4 MA plasma current. An advantage of a decoupled system over one that is not is that the OH and EF controls are independent of each other.

A 50 ms risetime requires about 1-kV loop voltage. To stay within reasonable state-of-the-art technology of large coil fabrication and switching (specification 5), the maximum coil voltage should be limited to about 50-kV. Hence the number of OH coil turns should be about 50. But simulations argued the need for more than 10 MA-turns in the OH coil to obtain required volt-seconds or with 50 turns the OH coil current must be about 200 kA, a value too large for presently available, reasonable cost, opening switches. The solution to this dilemma, taken from the Padova RFX design, consists of four interleaved coil sections in series, with each section made up of 64 OH turns in parallel with 64 turns from each of the four EF coil pairs. The number 64 was a compromise in meeting the constraints of the design.

The combination of specifications 2 and 4 forced the selection of the number and size of the TF coils. With 48 coils, access was sufficient but the mean minor coil radius to meet specification 4 is 60 cm. Because of the large radius of the TF coils and specifications 2 and 3, the EF coils could not be placed close to the liner, and simple methods for locating EF coils to optimize coupling and passive equilibrium from induced EF currents could not be employed. An advantage of the outward location of the EF coils is that fewer are needed to meet specification 3. Only three coil pairs could have been used. To improve the capability of the equilibrium control system four pairs are used.

There are several important consequences to the placement of EF coils relatively far from the liner compared to the ideal location on the liner. The greatest disadvantage of the ZTH EF coil location is a nonnegligible increase in OH coil and energy system cost over an ideal configuration, but a significant advantage is the reduction in the size of EF coils. A large leakage inductance results from this EF coil location that reduces the ZTH transfer efficiency to 60 per cent of the ideal maximum value, requiring a 40 per cent increase in OH coil volt-seconds and power over that for the ideal geometry. The leakage inductance also reduces the induced ampere-turns in the EF coils, and for ZTH this reduction results in forces on the EF coils that are less than one-half that for the ideal configuration. As a consequence, the ZTH EF coils are smaller and require less equilibrium power to supply resistive losses compared to the ideal geometry. ZTH EF coils could provide equilibrium for a plasma current of 6 MA with additional support against bending.

Selection of the plasma major radius required many iterative calculations to satisfy the specifications. It would have been desirable to calculate accurately the total experiment cost as a function of major radius R. But many functions required for this calculation are difficult to quantify. For example, the effort required to design the coil and load assembly tend to increase with decreasing R but in quantized steps. A recent attempt to decrease R from 2.4 m would have caused interference between TF coils and the support bulkheads, requiring a different and more expensive structure.

Opening switch rating had the greatest effect on the determination of R. Volt-seconds consumed by the plasma during current rise probably varied directly with  $\kappa$ . Magnetic energy transfer efficiency increases

with R to a power slightly less than one. Optimized OH coil inductance varies approximately as R (OH coil) to the 3/2 power. Combining these approximations leads to the conclusion that the required OH coil current varies roughly as  $1/R$ , a result with important implications regarding opening switch rating. At the onset of the ZTH magnetics design there was one proven opening switch design of reasonable cost rated at 25 kA, 50 kV. Testing of two of these switches in parallel for a 50 kA rating had been performed successfully at Los Alamos. A 75 kA switch is less reliable than the 50 kA tested switch and characteristics are not fully known. Selecting the ZTH opening switch rating at a nominal 50 kA set the OH coil inductance and hence the OH coil radius. The value of R then was determined by the spacing required for EF and TF coils and access specifications.

#### PF COIL OPTIMIZATION

Equilibrium power of the original ZT-II conceptual design is excessive at even 2 MA. A procedure is required that provides:

1. Low magnetic field in the liner region from the OH coils,
2. Decoupling of OH and EF coils so that induced EF currents are proportional only to plasma current,
3. Smaller EF currents for reduced forces leading to reasonable coil size,
4. Induced EF coil current distribution that meet flux surface deviation specifications for a specified Shafranov value, and
5. A coil arrangement that meets the diagnostic access specification and allows a reasonable structure.

Separate optimization of OH and EF coils does not yield the required decoupling of the two sets. Both must be optimized simultaneously. It would be desirable to minimize only one function (residual), the total cost of the experiment. But optimizer routines that minimize the sum of squares of residuals does not work, implying that working only with the total cost also will not work. A linear optimizer does not work. Nonlinear optimizer routines that minimize only one residual tend to get stuck in the maze of valleys and bayous of the hyperspace of the many variables.

The nonlinear optimizer subroutine that obtains satisfying results, written by Ken Klare of group ZTR-6 at LANL, is a modified Gauss-Newton procedure that operates, using both Jacobian and Hessian matrices, on all of the residuals simultaneously. The modifications include the addition of a hook feature that allows the routine to bypass Jacobian singularity difficulties. Previously tried optimizer routines are unsatisfactory because solution residuals and variables depend on the initial values and require many different starting points to approach the best solution. The Klare routine arrives at the same solution for a wide range of starting values, a result that provides confidence that the solution is the best possible for the constraints of the problem.

About 80 per cent of the optimizer programs evaluated the residuals, and most of the rest was the optimizer subroutine. The program was run in several different forms with 13 to 20 variables. Initially a set of 16 OH coil pairs obtained a field within the liner of less than 1 kG. But interleaving was difficult and the cost of 16 sets of tooling for fabrication would have been too expensive. With a proper set of 15 variables and 69 weighted residuals, the optimizer obtained a reasonable compromise that met the specifications with only 5 OH coil pairs.

Figure 1 shows the coil locations. Variables are the radius of coils 1 through 4, and 6, the height above the midplane of coils 2, and 4 through 8, and the four EF coil induced currents. The radius of coil 7 and height of 9 are fixed by access requirements. Because the optimizer tends to increase the radius of 5 beyond that which fits through the torus hall door, its radius is fixed. Similarly, the height of 3 is fixed because the optimizer wishes to locate it where it interferes with the torus hall crane. To minimize leakage inductance, coils 8 and 9 are placed as close to the TF coil as tolerance requirements allow.

The residuals are:

1. magnitude of B resulting from OH coil current at 23 points on the liner,
2. variation of flux due to EF and plasma currents at 23 points on the liner,
3. variation EF and plasma current flux at the EF coils,
4. variation of the elements of the first column of the inductance matrix from a specified input parameter, the desired OH value,
5. four coupling coefficients between OH and EF coils,
6. difference between induced EF currents and those required for minimum deviation of the flux surface at the liner,
7. difference between induced EF currents and a specified distribution,
8. two penalty functions to prevent the optimizer from causing structure problems by placing coils 2,3,6 too close to each other.

The redundancies in some of the residual functions are necessary. Transfer efficiency is approximately proportional to the OH coil inductance of 4 above. This parameter is as large as possible in the compromise to meet the specifications. For calculating the flux surface deviation, (d) the plasma current is represented as a single filament located at a radius equal to 1.003 R. This location is chosen to obtain the least d with EF coil currents that provide an index of about 0.3 and a vertical field (HV) calculated from

the Shafranov formula for A equal to -0.3. A solution of the full Grad-Shafranov equilibrium equations confirmed the adequacy of the approach<sup>2</sup>. The immobile single wire plasma representation provides the best test of the capability of the EF coils to form a minimum deviation flux surface. Effects of the shell and liner on flux surface deviation are not included. The inductance matrix is calculated with the liner forced to be a flux surface. Residuals 7 above are used to reduce current in the outer EF coils to minimize forces and hence size of these coils.

#### RESULTS OF THE OPTIMIZATION

The Gauss-Newton-hook optimizer routine works so extraordinarily well that it not only solves the required problem but also allows the reduction of the number of OH coils to five pairs, simplifying the structure and reducing the total OH coil cost. The greatest optimizer weight is placed on decoupling and achieving passive equilibrium at the initiation of plasma current. This weighting and the reduction of the number of OH coils does not obtain an ideal low value of residual B field within the liner due to OH coil current. Maximum calculated B within the liner is 10.4 mT. However, with 282 amperes in the trim coils at initiation of plasma current, the hexapole null shown in Fig. 1 is obtained.

Coupling coefficients between EF and OH coils varies from 3.E-6 for EF6 to 1.E-4 for coil EF8. These coefficients, which ideally should be zero for complete decoupling, are unrealistically small because of tolerance and nonideal winding effects. Induced EF coil currents caused by plasma current are within a few per cent of those from a Grad-Shafranov equilibrium calculation<sup>2</sup>.

Table 1 lists sensitivity factors for errors in coil fabricated radius or in placement. The first 9 rows are for a 1 cm increase in coil radius and the last 9 rows are for a 1 cm increase in height location above the midplane, all taken one at a time. The first 4 columns are multipliers of the decoupling coefficients, and the next 4 columns apply similarly to the coupling coefficients between EF coils and plasma. The last two columns are multipliers of the residual B within the liner due to OH coil current and multipliers for flux surface deviation. For example, if the radius of coil 2 is increased by 1 cm over the design value, the decoupling coefficient would change sign and increase in magnitude by a factor of 464. Similarly, the coefficient of coupling between plasma and coil 6 decreases 1 per cent, magnitude of B within the liner due to OH current increases 10 per cent, but flux surface deviation does not change.

A 50 per cent increase in B within the liner, because of a 1 cm error in the radius of coil 1, can be offset by initial trim current. Obviously, the decoupling factors are most sensitive to coil errors, yet the equilibrium supplier can take care of decoupling factors as large as 0.004 with the 50 ms shell time constant. The mean copper radius of each coil will be determined as accurately as possible and the optimizer will be used to determine offsets in the coil heights above the midplane to recover the best realistic decoupling. A calculation shows that such adjustment would be successful. All coils can be adjusted 2 cm in height from the midplane to correct for radius errors and in eccentric displacement to compensate for eccentric location of copper within the mold. Each coil block shown in Fig. 1 actually consists of four sections with separate leads for interleaving. In each block the coil sections are rotated 90 degrees with respect to each other to reduce

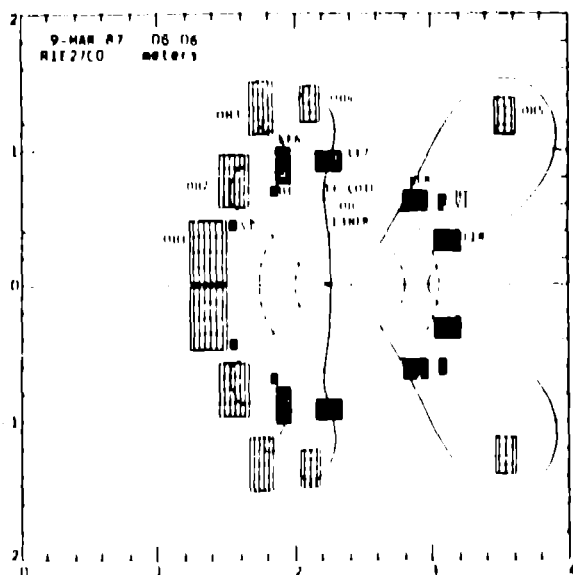


FIG. 1. Outline of coils and flux surface for a charged OH coil with 282 A current in the trim coils.

Table 1

## ZTH COIL SENSITIVITY FACTORS

	Sensitivity factors for a 1 cm increase in R taken one at a time				I(oh) coils of Ief				max  B  liner	flux surface deviation
	1	2	3	4	1	2	3	4		
1	327.8	30.1	-0.3	3.2	0.99	1.00	1.00	1.00	1.3	1.0
2	-463.5	11.6	0.1	2.8	0.99	1.00	1.00	1.00	1.1	1.0
3	56.8	20.2	-0.1	4.1	1.00	1.00	1.00	1.00	0.8	1.0
4	144.1	50.5	2.9	-1.0	1.00	1.00	1.00	1.00	0.8	1.1
5	38.5	-9.1	-0.5	-1.4	1.00	1.00	1.00	1.00	1.0	1.0
6	-95.8	-6.1	1.0	1.0	1.01	0.99	1.00	1.00	1.0	1.0
7	-31.8	-18.3	1.4	0.7	1.01	1.00	1.00	1.00	1.0	1.0
8	1.5	-0.7	2.0	2.2	1.00	1.01	0.97	1.00	1.0	1.1
9	1.0	1.1	1.1	1.3	1.00	1.00	1.02	0.97	1.0	1.3

## Factors for a 1 cm increase in Z

1	-268.7	14.5	1.5	0.3	1.00	1.00	1.00	1.00	0.9	1.0
2	-302.4	13.2	0.8	2.1	1.01	1.00	1.00	1.00	0.7	1.0
3	263.0	21.9	2.5	-1.6	1.00	1.00	1.00	1.00	0.9	1.0
4	110.3	-38.4	1.9	-0.5	1.00	1.00	1.00	1.00	1.0	1.0
5	-78.0	6.7	-0.3	6.4	1.00	1.00	1.00	1.00	1.1	0.9
6	42.3	3.9	1.0	1.0	0.94	1.01	1.00	1.00	1.0	1.0
7	12.5	7.7	0.9	1.1	1.01	0.96	1.01	1.00	1.0	1.0
8	0.8	1.3	0.8	0.8	1.00	1.00	0.98	1.02	1.0	1.1
9	1.1	0.6	0.7	-0.5	1.00	1.00	1.00	0.99	1.0	1.2

nonaxisymmetric effects such as crossovers and leads. Copper conductor skin effects are not included, but calculations show that skin effects are not a problem.

A large number of 0-D Culham coupled model simulations were undertaken during the magnetica development to insure that SCR type power supplies of reasonable size could be used. The circuits program SCAT was employed for all simulations. Figure 2 shows some of the outputs of one simulation where supplies attempt to maintain a constant plasma current (2a) of 4 MA following inductive energy transfer and attempt to maintain a constant value of  $\theta$  by feedback control of the B-phi SCR supply. Figure 2c shows d, the flux

surface deviation, where I-phi is represented as a single filament as discussed above. An ad hoc plasma resistance function was chosen so that I-phi reached 2 MA at the end of inductive energy transfer (4 Vs at the liner, Fig. 2e). This function is inversely proportional to I-phi (constant resistive voltage) and decreases as F passes through zero, characteristic of ZT-40M data. Variable I(oh) of Fig. 2g is the OH coil current, where the four sections are in parallel for a more simple circuit representation (4 times 50 kA at  $t = 0$ ).

A test of the magnetica design was a simulation using a model that approximates plasma motion to determine if the EF coils and supplies control equilibrium if, for example, the Shafranov A changes rapidly. For this model the shell, liner, and plasma are each represented by 24 pairs of filaments or wires, located symmetrically about the midplane. The simulation with realistically modeled SCR supplies shows that flux surface and equilibrium control is obtained with a simple feedback algorithm having a preprogrammed input.

## CONCLUSION

A method, devised to optimize ZTH OH and EF coil locations, provides a design that meets specifications including minimizing costs. Several types of circuit simulations show that the design will be capable of plasma boundary flux surface control with EF supplies rated at a power level only slightly greater than that required to supply resistive losses for the maximum current rating of the EF coils. EF coil current rating is 25 per cent greater than the currents required for equilibrium at 4 MA and Shafranov A of -0.1.

## ACKNOWLEDGMENTS

We acknowledge the contributions of the Los Alamos RFP team for discussion and reviews of this effort, in particular that of D.A. Baker, J.N. DiMarco, H.J. Boenig, A.J. Giger, K.A. Klare, L.W. Mann, J.G. Melton, G. Miller, J.A. Phillips, M.M. Pickrell, and K.F. Schuenberg. Work performed under the auspices of the US DOE.

## REFERENCES

- [1] G. Malewani, G. Rostagni, "The RFX Experiment," *Proc. of the 14th Symposium on Fusion Technology*, Avignon, 1986, pp. 173-184.
- [2] D. Baker et al, "ZTH Equilibrium," *Proc. RFP Workshop*, Los Alamos, July, 1987, LA-11139-C, pp. 183-200.
- [3] R. Gribble, "ZTH Magnetica Design," *Ibid*, pp. 163-182.

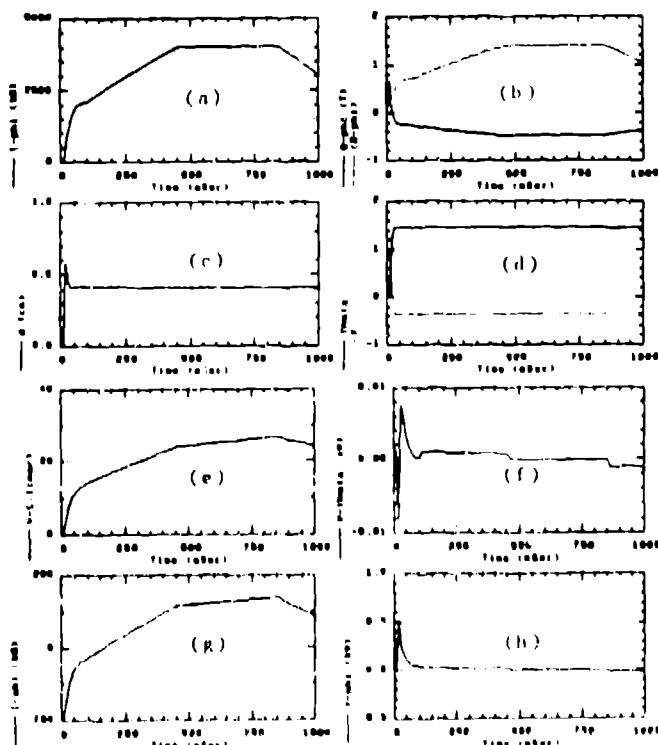


Fig. 2. 0-D simulation results of the ZTH configuration.